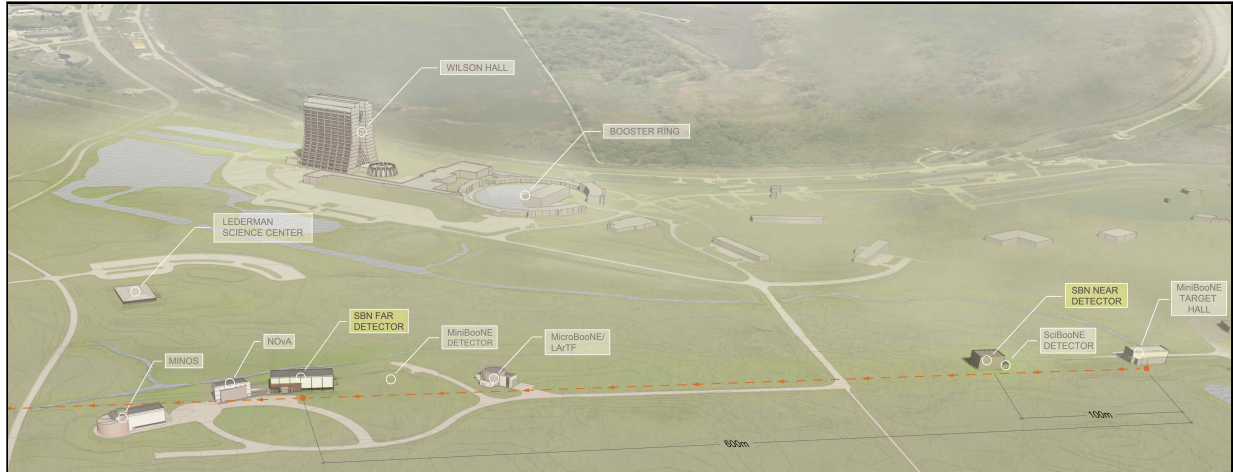# A Proposal for a Three Detector
Short-Baseline Neutrino Oscillation Program
in the Fermilab Booster Neutrino Beam

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The ICARUS-WA104 Collaboration

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I. INTRODUCTION

We propose a Short-Baseline Neutrino (SBN) physics program of three LAr-TPC detectors located along the Booster Neutrino Beam (BNB) at Fermilab. This new SBN Program will deliver a rich and compelling physics opportunity, including the ability to resolve a class of experimental anomalies in neutrino physics and to perform the most sensitive search to date for sterile neutrinos at the eV mass-scale through both appearance and disappearance oscillation channels. Additional physics of the SBN Program includes the study of neutrino-argon cross sections with millions of interactions using the well characterized neutrino fluxes of the BNB. The SBN detectors will also record events from the off-axis flux of the NuMI neutrino beam with its higher electron neutrino content and different energy spectrum. Finally, the SBN Program is an excellent opportunity to further develop this important technology for the future long-baseline neutrino program while utilizing its remarkable capabilities to explore one of the exciting open questions in neutrino physics today.

The recent report of the Particle Physics Prioritization Panel (P5) specifically recommended a near-term, world-leading short-baseline experimental neutrino program with strong participation by the domestic and international neutrino physics communities working toward LBNF:

- P5 Recommendation #12: In collaboration with international partners, develop a coherent short- and long-baseline neutrino program hosted at Fermilab.

- P5 Recommendation #15: Select and perform in the short term a set of small-scale short-baseline experiments that can conclusively address experimental hints of physics beyond the three-neutrino paradigm. Some of these experiments should use liquid argon to advance the technology and build the international community for LBNF at Fermilab.

This proposal outlines exactly such a program. The SBN program brings together three LAr-TPC detectors built and operated by leading teams of scientists and engineers from Europe and the U.S. The ICARUS-T600 detector is the first successful large-scale LAr-TPC to be exposed to a neutrino beam and to this point the largest LAr-TPC for neutrino physics. The MicroBooNE detector is the largest LAr-TPC built in the U.S. and will have been operational for several years at the start of the three detector program. The new near detector, LAr1-ND, is being developed by an international team with experience from ArgoNeuT, MicroBooNE and LBNE prototypes. The combination of these three detectors and associated collaborations represents a tremendous R&D opportunity toward the future LBN program.

At the January 2014 meeting of the Fermilab PAC, presentations were made by two collaborations to significantly enhance the physics capabilities of the Booster Neutrino Beam (BNB) with additional LAr-TPC detectors. Both proposals were targeted at providing definitive measurements of the LSND and MiniBooNE anomalies. The ICARUS collaboration proposed [1] a two detector experiment incorporating the existing T600 LAr-TPC located 700 m from the BNB as a far detector and a new T150 LAr-TPC located 150±50 m from the target as a near detector. The primary physics goal of the ICARUS proposal was the search for light sterile neutrinos. The idea to utilize multiple LAr-TPC detectors for a comprehensive test of neutrino anomalies was first put forth by the ICARUS collaboration at CERN as early as 2009 [2–4] and later extended to include the addition of magnetized spectrometer detectors [5] by the NESSIE collaboration. The ICARUS-NESSIE proposal [6] required the construction of a new neutrino beam (CENF) from the 100 GeV proton SPS in the CERN north area, which has not since been realized.

Also at the January 2014 Fermilab PAC meeting, the LAr1-ND collaboration proposed [7] to install a new LAr-TPC based on LBNE-type technology 100 m from the BNB target in an existing enclosure that was constructed for the SciBooNE experiment. The proposed LAr1-ND detector, in concert with the MicroBooNE experiment, would address the MiniBooNE neutrino mode anomaly and enable improved searches for oscillations. LAr1-ND was seen as the next step in a phased short-baseline neutrino program at Fermilab. The full LAr1 detector, a 1 kton LAr-TPC previously presented in an LOI in 2012 [8], could then, together with LAr1-ND, definitively address the question of neutrino oscillations in the $\Delta m^2 \approx 1$ eV^2 region. LAr1 was not encouraged by P5, however, due to the high cost of a new detector of this scale.

Following the recommendation of the PAC, the MicroBooNE, LAr1-ND, and ICARUS collaborations were asked by the Fermilab Director to propose a combined Short-Baseline Neutrino (SBN) program to address the short-baseline anomalies and search for sterile neutrinos. The SBN Task Force was created to steer the activities of the collaborations required to create this proposal including a conceptual design for the program components. The task force was charged jointly by the directorates of CERN, Fermilab, and INFN. The task force consists of five members, one representing each of the three collaborations (LAr1-ND, MicroBooNE, ICARUS), one representing CERN, and the Fermilab SBN Program Coordinator. This proposal is the result of this joint effort over a period of about nine months. The proposal is organized into six parts that are briefly summarized below.

Part 1 describes the primary physics case for the SBN program: the search for sterile neutrinos and exploration of the LSND and MiniBooNE anomalies. This chapter describes the physics motivations including the current landscape of oscillation anomalies at the $\Delta m^2 \sim 1$ eV^2 scale. The physics sensitivity for ν_μ disappearance and ν_e appearance are evaluated for the proposed three detector configuration. The extensive evaluation of systematics includes the impact of neutrino interaction uncertainties and differences in the neutrino flux at the different detectors. The primary backgrounds to the ν_e signal have been carefully considered in the sensitivities:

- Intrinsic ν_e content of the beam,

- Neutral current γ production,

- ν_μ charged current γ production,

- Neutrino interactions in material surrounding the detectors,

- Cosmogenic photons.

Using data sets of 6.6×10^{20} protons on target (P.O.T.) in the LAr1-ND and T600 detectors plus 13.2×10^{20} P.O.T. in the MicroBooNE detector, we conservatively estimate that a search for $\nu_\mu \rightarrow \nu_e$ appearance can be performed covering with $\sim 5\sigma$ sensitivity the LSND allowed (99% C.L.) region. This level of sensitivity is achieved using relatively simple event selection criteria that have undergone only a preliminary optimization. A more detailed analysis will likely yield even better results. However, achieving this level of sensitivity will require careful control over cosmogenic backgrounds. The external muon tagging/veto systems proposed in Parts 2 & 3 of this proposal will be essential in ensuring an efficient independent method of identifying tracks in the TPCs associated with cosmogenic muons. Further, requiring precision timing of the already planned light detection systems will play an important role in rejecting cosmogenic photons. Since the measurement is statistically limited, an increase in the number of ν interactions provided by more protons on target and/or greater efficiency of the target/horn

system will be highly desirable. Part 5 of this proposal outlines a possible reconfiguration of the BNB with a two horn system.

Part 2 describes the conceptual design of the SBN near detector (LAr1-ND) which will be located 110 m from the BNB target. The detector design draws extensively on the design of the LBNF far detector including cryostat technology, TPC design, and electronics. Also described are the synergies between LAr1-ND and the LBNF development. Potential benefits include expanded experience in construction of membrane cryostats, development of standardized cryogenic system modules, wire plane assembly techniques, testing of next generation cold electronics, and the development of scintillation light collection systems for LAr-TPCs. A system of scintillators external to the cryostat are proposed to provide a system for identifying tracks from cosmic rays. The near detector has been approved by Fermilab as a test experiment (T-1053).

Part 3 describes the SBN far detector (ICARUS-T600), presently the largest physics oriented operational LAr-TPC detector [9], and its very successful performance during operations in the Gran Sasso laboratory (LNGS) on the CNGS beam. The T600 will be located 600 m from the BNB target. In preparation for a thorough refurbishing, the T600 was transported from LNGS to CERN at the end of 2014. The light detection system will be improved with many additional photo-multipliers to provide better timing resolution and spatial segmentation of the light signals. These improvements are essential to handling the much higher flux of cosmic rays through the detector with operation near the surface on the BNB. Like the near detector, counters surrounding the sensitive LAr-TPC volume are proposed to provide a system for identifying tracks from cosmic rays. These cosmic tagger systems provide a clear opportunity for shared development within the SBN program.

Part 4 describes the conceptual design of infrastructure needed for the LAr1-ND and T600 detectors. This includes construction of two new detector enclosures on the beamline at 110 m and 600 m from the BNB target for the near and far detectors, respectively. Each of the detectors will be located on axis with the BNB. The design of the new detector cryostats and cryogenic systems are also described. The new cryogenics infrastructure is being developed by a joint team of engineers at CERN, Fermilab, and INFN taking advantage of opportunities for common solutions for the two detectors. While a completely new LAr filtration and circulation system is needed for the near detector, the LAr systems used at LNGS for the T600 will be reused. A possible model for a common DAQ software platform for the detectors is described. Similarly, a model is described for common reconstruction and analysis tool development based on the presently working algorithms from the ICARUS-T600 experience and the LArSoft platform currently in use by ArgoNeuT, MicroBooNE, and the LBNE 35 ton prototype.

Part 5 describes potential improvements to the Booster Neutrino Beamline. A modest reconfiguration of the beamline leading up to target and horn could provide sufficient space to convert the beamline from a single horn to a two horn system. An optimization based on a fast simulation demonstrates that the ν_μ rate can be approximately doubled relative to the existing MiniBooNE horn. A more detailed study is required to take this pre-conceptual design to a conceptual design that could be used to estimate cost and schedule to create a two horn configuration. Such an improvement would be an extremely valuable addition to the program providing headroom on the statistical power of the measurements. We propose that a detailed study of the cost and schedule for conversion to a two horn system be initiated immediately. This should include the cost of new horns, new or refurbished power supplies capable of 20 Hz operation, and necessary work for reconfiguration of the incoming beamline and of the collimator.

Part 6 describes the organization of the SBN program and the schedule for completion of

the detectors. A set of high level milestones is shown that has installation of both the near and far detectors during 2017 culminating in the three detector configuration ready for beam data-taking in the spring of 2018. Funding for the program is expected from a combination of US DOE, US NSF, and international in-kind contributions. The overhauling, improvements, and transport of the ICARUS-T600 is a major contribution of INFN and of CERN in terms of equipment and of associated funding to the realization of the present program. Commitments are already in place for funding from CERN, INFN, and UK-STFC. Funding is being sought from CH-NSF and discussions are in progress with other international partners. Organization of the program draws upon the very successful model of the LHC experiments at CERN. Under the proposed structure, the program will be monitored by an oversight committee organized by Fermilab on behalf of the international partners.

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